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Geothermal potential analysis using 3d modeling of subsurface structures based on the Gravity Anomaly in the Mount Lawu Area, Central Java

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ABSTRACT

Over time, the needs of energy will continue to increase. Dependence on the use of fossil energy results in the availability of such energy will run out at any time, so it is necessary to develop research on geothermal energy that is environmentally friendly and renewable. One of the Geothermal Work areas is on Mount Lawu, located at coordinates between 111°15' east longitude and 7°30' south latitude in several districts Central Java Province and East Java Province. The purpose of this study is to provide information related to geothermal potential using the gravity method by knowing the temperature of the area and the 3D modeling of subsurface structures. Based on the results of the analysis Second Vertical Derivative (SVD) found three normal faults located in geothermal sources and modeling results the residual anomaly map depicts the distribution of high anomaly between 2 mGal up to 6.5 mGal scattered in the North to South, and East to West which is suspected to be lava rock intrusion. The results of the 3D inversion model show there are three layers, namely clay rock, which is suspected to be cap rock at a depth of 500 - 2500 m, pyroclastic lava rock, which is suspected to be as a reservoir at a depth of 3000 - 4500 m, and lava, which is suspected to be as a reservoir heat source at a depth of 5000 - 8000 m. Based on the map in Land Surface Temperature (LST) obtained the temperature value of Mount Lawu ranging from 3.14 °C - to 23.25 °C.

Keywords:
Geothermal energy; Mount Lawu; gravity method; 3D inversion; Land Surface Temperature (LST)

Introduction

Indonesia is located in an area with a series of active volcanoes because Indonesia is located at the confluence of three active tectonic plates, the Eurasian, Indian-Australian, and Pacific plates so the geothermal energy is abundantly available (Hall R & Blundell, 1996). Around 40% or 29,000 MW of the world's total geothermal energy is in Indonesia, but the utilization of geothermal areas in Indonesia has not been maximized. Geothermal energy is heat energy that is formed beneath the earth's surface naturally, where natural heat energy originating from the earth is trapped quite close to the surface and can easily be exploited economically (Bodvarsson & Witherspoon, 1989). According to (Dwikorianto & Ciptadi, 2006) the main components forming a geothermal system include heat sources, reservoirs, clay caps, and fluid circulation. Freezing magma as a heat source produces igneous rock which conductively transmits heat to the surrounding rocks. Then the heat propagates to heat the fluid in the reservoir (Luthfi et al., 2020). A reservoir is a place where heat-carrying fluid accumulates which is covered by a covering layer. Reservoirs are composed of permeable rocks. Meanwhile, geothermal fluid can be water or hot steam (Dickson & Fanelli 2003).

The development of geothermal energy exploration for use in daily life is certainly very much needed considering the availability of fossil energy which is not proportional to the increasing human needs. Geothermal energy can have great opportunities because this energy source is stored in the bowels of the earth so that it is considered to be able to produce sustainable energy and will never run out. Even in its development, this energy includes energy sources that do not cause excessive emissions (Meilani & Wuryandani, 2010).

One of the geothermal areas that have the potential for geothermal energy is the Mount Lawu area. This strato-type volcano which located on the border of East Java and Central Java Provinces. The area of Mount Lawu is in a quarter volcanic area with pyroclastic andesite rocks as its constituent rocks. This supports the emergence of geothermal manifestations such as hot springs around Mount Lawu therefore it is suspected that this area has a geothermal system (Hermawan & Permana, 2018).

This research was conducted to provide information related to geothermal potential using the gravity method by knowing the temperature of the area, knowing the distribution of residual gravity anomalies, knowing the subsurface structure using First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) as well as knowing the 3D modeling of subsurface structures.

General Principles of the Gravity Method

General Principles of the Gravity Method The gravity method is one of the methods used in the early stages of geophysical studies based on differences in variations in the subsurface gravity field. The basic principle used in the gravity method is Newton's law of gravity, which states that each part of an object will cause an attractive force on the part which is equal to the product of the masses and inversely proportional to the square of the distance between the two masses (Grandis, 2009). The magnitude of the attractive force between two particles of mass M and m is shown by the equation:

$$F = \gamma \frac{Mm}{r^2} \tag{1}$$

Where F is the attractive force between two objects M and m, Mm is the mass of the earth and the mass of the object, γ is a gravitational constant which has a value of 6.67×10^{-11}Nm^2/Kg, and r is the distance between the two particles.

In the gravity method, measurements are made of the value of the vertical component of the acceleration due to gravity somewhere. But in reality, the shape of the earth is not spherical so the value of the acceleration due to gravity varies from one place to another. Factors that can affect the value of the acceleration of gravity include differences in latitude, height (topography), the position of the earth in the solar system, changes in the density of rock mass below the surface, where the difference in height measured can affect the value of gravity and other factors such as buildings and so on(Telford, G., Sheriff, & Keys, 2016).

Gravity Method Correction

In using a gravity meter for measurement, the value of the gravitational acceleration measured on the gravity meter still has influencing factors. While the gravity value sought is a value that is not influenced by other factors, or in other words it has been corrected (Araffa et al., 2015). Corrections that must be made are:

Free Air Correction

Newton's law states that the gravitational force's value is inversely proportional to the square of the distance between two objects. Therefore, the higher the distance from the Earth's subsurface, the smaller the acceleration due to gravity, given the greater distance from the center of the Earth to the measurement point. In normal gravity correction, the object is assumed to be at the reference point. However, in reality, gravity measurements are usually conducted in areas high above mean sea level. Due to the height difference, the gravity meter reading must be corrected. The average change in gravity with altitude is 0.3086 mGal/m (Latifah, 2010). Free air correction formulated by the equation:

$$FAC = 0.3086 \ \times h \qquad (2)$$

Where FAC is the free air correction (mGal), and h is the height of the very point above sea level (m).

Bouguer Correction

The Bouguer correction depends on the height of the extreme point from the datum plane and the rock mass density between the extreme point and the datum plane. The value of the Bouguer correction is the opposite of the free air correction, subtracting if the point is very above the datum plane and adding up if the point is below the datum plane (Burger, 1992). Bouguer correction (CB) is expressed in equation (Telford et al., 2016)

$$Bc = 0.04193 \times \rho \times h \qquad (3)$$

Where's the Bouguer mass density is the height of the measurement point from the spheroidal plane.

Terrain Correction

Terrain correction becomes necessary in areas where gravity measurements are taken on uneven surfaces, such as valleys, where the gravitational acceleration value at the specific point is decreased. Conversely, the presence of hills results in a significant reduction in the acceleration of gravity at that point, as the hill mass generates an upward force component opposing gravity. Consequently, the existence of hills and valleys diminishes the true gravitational field strength at a given point. As a result, the calculated field correction is consistently positive. This correction is derived through the acquisition of field data, which is subsequently processed using the Hammer Chart method (Isroi, 2014). Meanwhile, for satellite imagery gravity research that does not take data directly into the field, global mapper and oasis montaj software is used to obtain field correction values. The field correction can be written in the equation:

$$\delta g_T(r,\theta) = \gamma\rho\theta \ \{(r_0 - r_i) + \sqrt{(r_i^2 + \Delta z^2} - \sqrt{(r_0^2 - \Delta z^2)} \qquad (4)$$

Where δg_T is the field correction (mGal), Δz difference in elevation of the compartment (m), γ is the universal gravitational constant, r_o and r_i is the radius of the outer and inner circle (m), and θ is the angle formed by the compartment (degrees)(Lewerissa, 2020).

First Horizontal Derivative

The First Horizontal Derivative, also known as the Horizontal Gradient, refers to the initial horizontal change in a gravitational field. A horizontal Gradient Gravity anomaly arises from a mass that tends to reveal the boundaries of that mass. Consequently, the FHD method proves useful in identifying the position of the contact boundary for horizontal density contrast in gravity data (Zaenudin, Sarkowi, & Suharno, 2013). Derivative analysis uses the First Horizontal Derivative (FHD) filter to determine the location of the horizontal density contrast contact boundary from the force data (Yulistina dkk., 2020).

Second Vertical Derivative

The utilization of Second Vertical Derivative (SVD) is essential for identifying the location and nature of both descending and ascending faults (Hartati, 2012). This technique involves a double reduction of gravity data in the vertical direction (Reynold, 1997). Executing the Second Vertical Derivative (SVD) serves the purpose of accentuating the localized impact of regional influences and delineating the boundaries of structures within the study area. This filtering process proves particularly effective in highlighting fault structures and resolving residual anomalies that might otherwise remain indiscernible through regional-residual separation techniques (Purnomo, Koesuma, & Yunianto, 2014).

Land Surface Temperature (LST)

The Earth's surface temperature is controlled by a balance of energy interactions among the surface, atmosphere, thermal properties of the surface, and subsurface materials. In remote sensing, land surface temperature is defined as the mean temperature of a specific area, represented by a pixel that can cover different types of surfaces (Faridah & Krisbiantoro, 2014).

Methods

The data used in this study comes from the GGMPlus satellite data in the form of gravity anomaly in the area of Mount Lawu in the districts of Karanganyar, Sragen, Wonogiri, Central Java Province, and Ngawi Regency, Magetan, East Java Province with coordinates 7°27' - 7°46' South Latitude and 111°1' - 111°20' East Longitude.

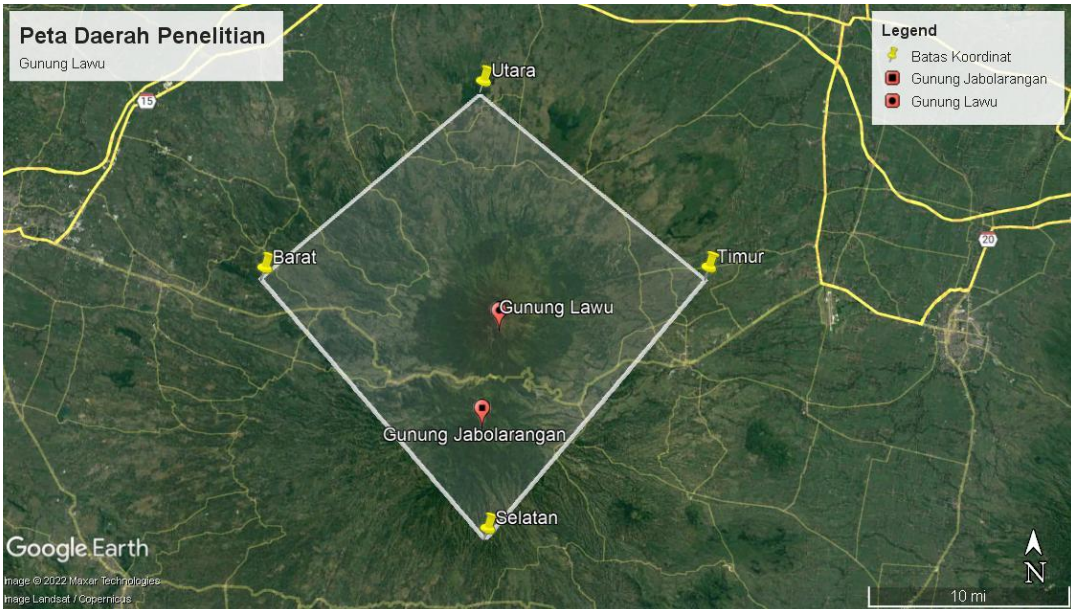


Figure 1. Research Area

This research was conducted using the gravity method in Mount Law area on the border of Central Java and East Java as show in Figure 1. The data used are secondary data originating from GGMPlus data. Data extracts carried out with Matlab obtained data in the form of gravity, DEM, and geoid values totaling 56760 data, then gravity correction was carried out in the form of Free Air Correction, Free Air Anomaly by using Microsoft Excel. For the field, a correction was carried out with the help of global Mapper software to obtain a grid of local and regional boundaries and assisted with Oasis Montaj software which then performed Bouguer correction. To obtain a complete anomaly value in an area, it is necessary to correct the earth's gravity field data with high resolution so that it is associated with the distribution of subsurface rocks. Based on the corrections that have been made, it is obtained a complete Bouguer anomaly map that needs to be separated from an anomaly using a Butterworth filter to obtain regional anomalies and residual anomalies by selecting points cut off between the residual (shallow) zone and the regional (deep) zone. then done slicing on the residual anomaly map to obtain conditions in the area that is close to the surface and 3D inversion modeling is carried out to see clearly. Inversion modeling is basically the process of modifying the model mechanism to obtain a better match between calculation data and observation data, carried out automatically (Rahma, 2012). The choice of the Butterworth filter is because the filter has a passband amplitude response that is almost flat (maximally flat) and has no ripples so it is relatively better than what is commonly used (Laghari, Baloch, Mengal, & Shah, 2014).

Results and Discussions

Based on the map of Land Surface Temperature (LST) in Figure 2 can explain the temperature surface range between 3.14°C – 23.25°C on Mount Lawu marked with the color blue. The data was taken from the USGS website on December 8, 2021. That thing was proven when the overlay between the LST map and the map of the research area where the highest temperature is around the research area where there are manifestations in the form of hot springs (Widodo, Kusnadi, Kholid, & Rezky, 2009) .

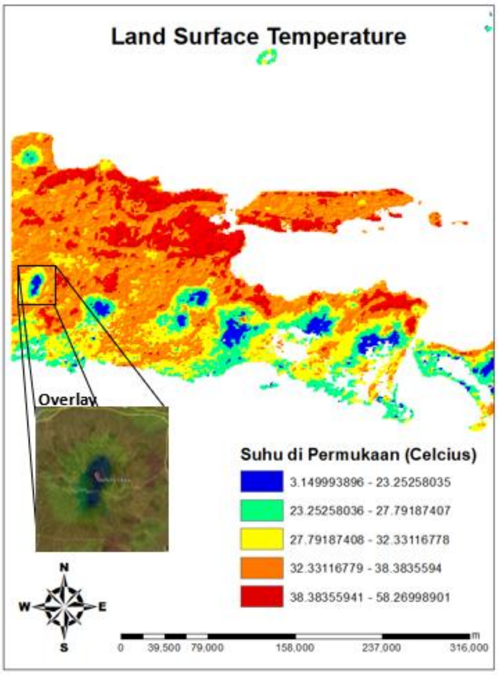


Figure 2. Land Surface Temperature (LST) Map

On gravity data processing GGMplus made several corrections so that the CBA value in Figure 3 was obtained with a range of -127.7 mGal - (36.6) mGal. As we can see, the low anomaly distribution is characterized by blue color with values ranging from -127.7 mGal to -21.5 mGal located at the peak of Mountain Lawu, which is estimated as the area of low anomaly associated with rock pyroclastic in the form of fractions of volcanic results from the eruption of volcano. High anomalies are characterized by pink and red colors that range from 8.5 mGal to 36.6 mGal, located at these high anomalies associated with extrusive lava. The lava flow comes from the Candradimuka crater, heading south, and fills the Cemorosewu graben.

Figure 4 shows the area DEM map Mountain Lawu. This DEM Map is a map topography that describes the shape surface of something in the form of height. The research area has a height between 129.3 m to 2125.5 m. Based on the results DEM map obtained, it is visible that the areas of Mountain Lawu topography low are next to the north area research which is low with 129.3 m to 308.3 m elevation and topography currently with height 329.5 m – 921.2 m. For an area with mark topography high is associated with plains height and area Mountain Lawu.

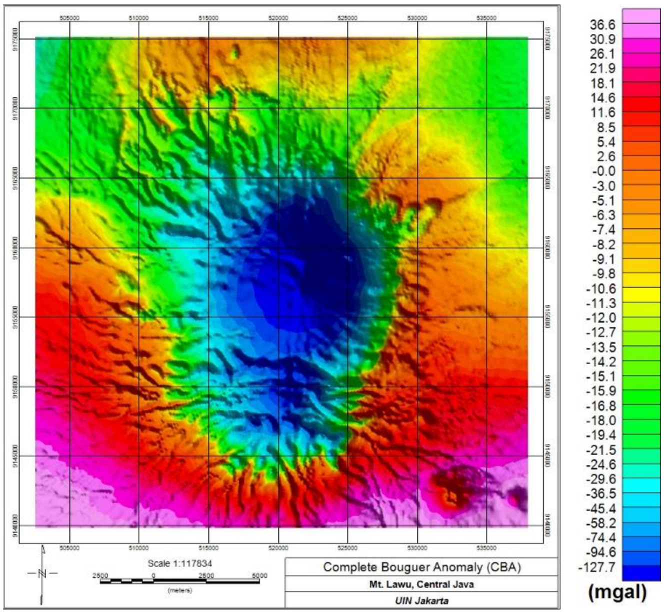


Figure 3. Complete Bouguer Anomaly (CBA) Map

Separation results from regional anomaly in Figure 5(a) obtained values ranging from -129.9 mGal to 36.0 mGal, and residual anomaly in Figure 5 (b) obtained values ranging from -7.3 mGal to 6.5 mGal.

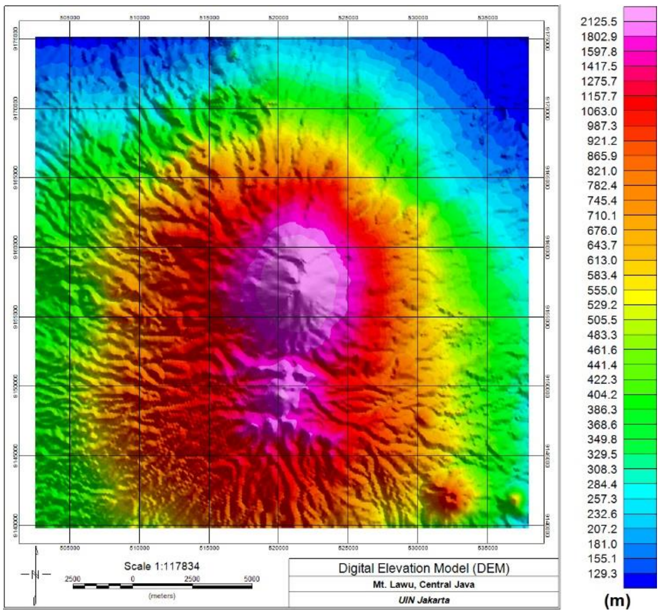
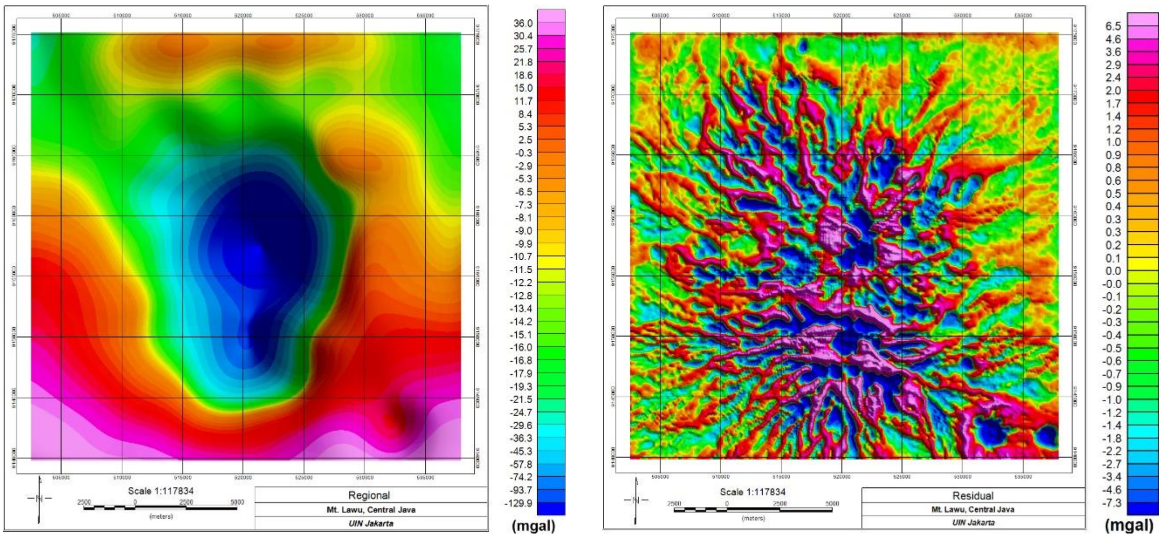


Figure 4. Digital Elevation Model (DEM) Map

Residual anomaly map resulting from the mathematical process of subtracting anomalous boogers from anomalous regions. In the separation process Among regional and residual anomalies are performed using a Butterworth filter, which is the filter easily made and does not need many components (Laghari et al., 2014).



(a) (b)

Figure 5. (a) Mountain Regional Map Lawu and (b) Mountain Residual Map Lawu

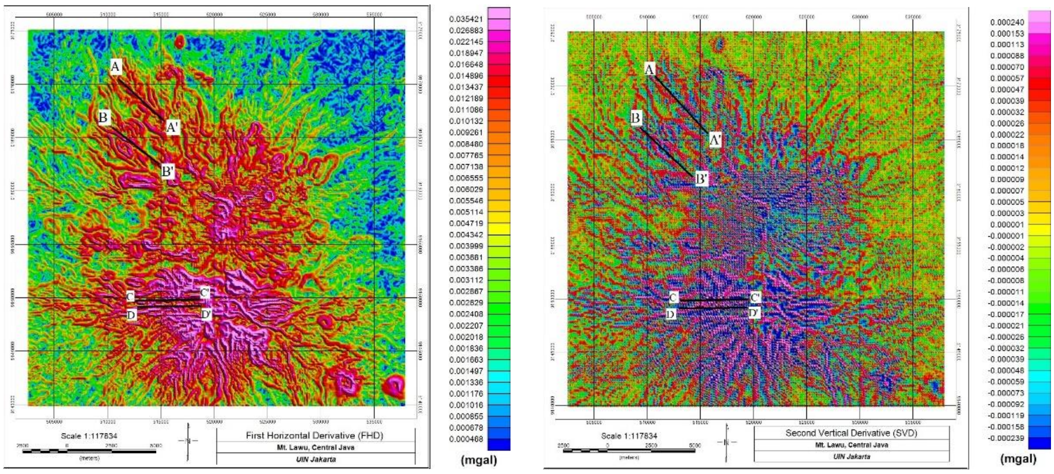
Compared to residual anomalies, regional maps form finer anomalies because scattering anomalies in regional layers are located in layers farther from the surface. Anomaly low on the regional map has range -129.9 mGal up to -24.7 mGal located at the peak Mountain Suspected Lawu related to rock breccia and tuff which are the product from sediment pyroclastic origin of volcanic material clastic results a series of eruption processes Mountain fire. Anomaly tall own range -9 mGal up to 36 mGal located west to the suspected south associate with andesitic lava. This lava originated from the magma that comes out from Mountain crater Candradimuka or the fault experienced freezing so that a little room is left blank for existing air (Amalisana, Rokhmatullah, & Hernina, 2017).

The residual map has more anomalies because scatter anomalies on this residual map are more closely with the surface. On the anomaly low, the own range mark ranges between -7.3 mGal up to -1.2 mGal and anomaly tall with range mark range between 2 mGal up to 6.5 mGal. The second anomaly is low and high, scattered around peak Mountain Lawu so that it consists of rocks that have low density compared with rock surroundings.

On the FHD map in Figure 6 (a), the gravitational range obtained for this scattering anomaly ranges from 0.000468 mGal to 0.035421 mGal. FHD filters with anomaly highest (0.022145 - 0.035421 mGal) seen that anomaly straightness or complex fault around hot springs Ngunut and Jenawi, which are located in the northwest where existence fault the be marked with the lines A - A' and B - B' which own northwest-southeast direction and fault surroundings hot springs the Tasin located next door south be marked with the line C - C' which has west-east direction.

On the obtained SVD map in Figure 6 (b), seen that scatter anomaly obtained gravity range between -0.000239 mGal up to 0.000240 mGal SVD filter with anomaly low (-0.000239 - (-0.000032) mGal) visible that anomaly straightness or very complex fault around hot springs Ngunut and Jenawi, which are located in the northwest where existence fault the be marked with lines A - A' and B - B' having northwest-southeast direction and fault surroundings hot springs Tasin, located next door to the south, is marked with there is a line C - C' which has direction east-west trending.

Existing faults are called intensified normal faults, and the study of geological data shows that the research on structural geological areas is dominated by ordinary normal faults trending northwest-southeast, east-west, and north-south. This normal fault is an expected manifestation of the exit number of hot springs around Mountain Lawu (Helmi, Kurniawan, Adam, Studi, & Geologi, 2020).



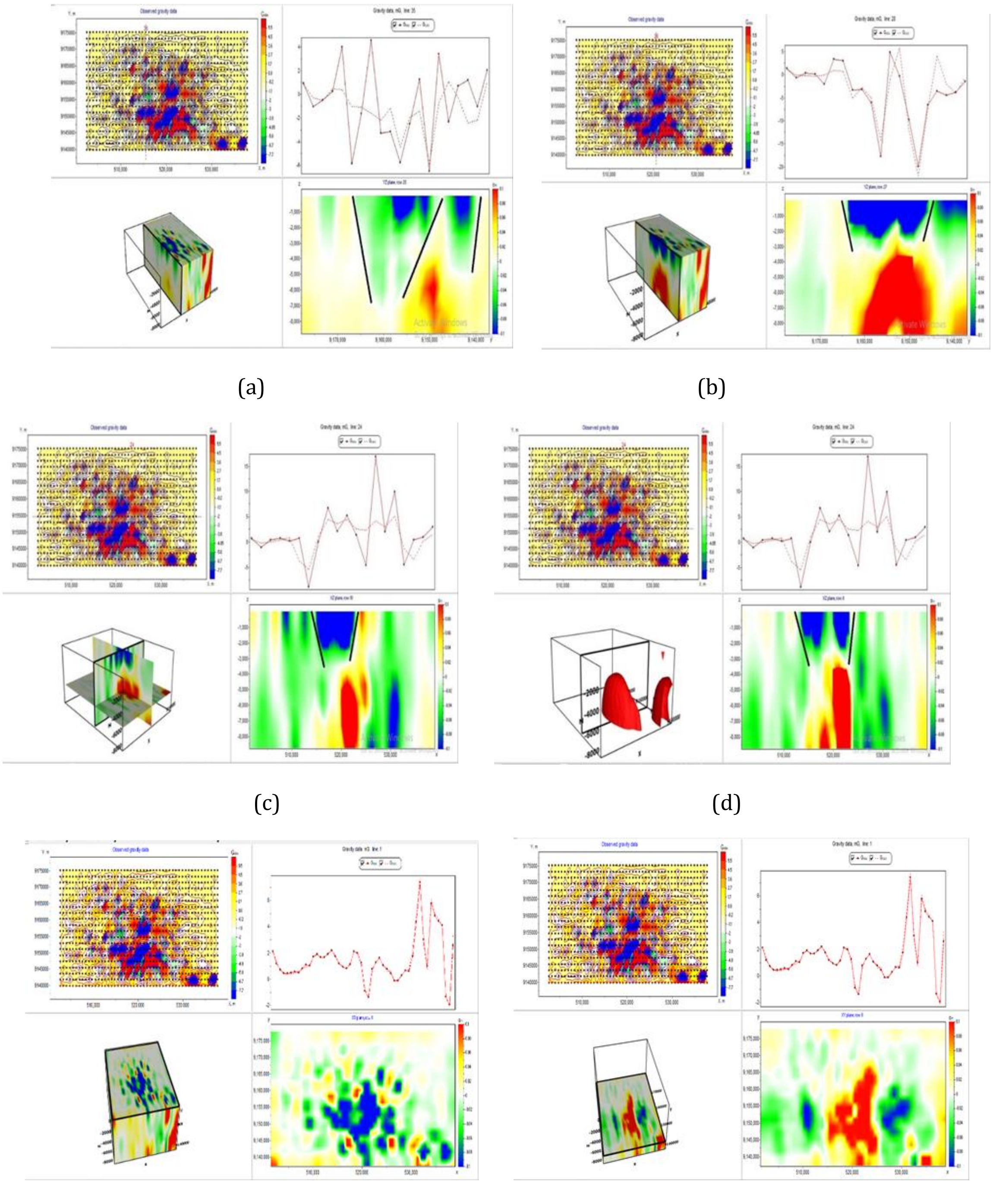
(a) (b)

Figure 6. (a) First Horizontal Derivative (FHD) Map, (b) Second Vertical Derivative (SVD) Map

Based on the results of 3D modeling (a) using ZondGM3D obtained RMS error of 46.2, presumably 3 faults show the manifestation of hot earth in the form of hot springs in the southwest area study as shown in figure 8. This is a geological wildfire according to the map of (Abdurrachman et al) the manifestation that appears on the side west slope of Mt Lawu is in unit Pra Lava flow Lawu 2 (PLI2) and Formation Notopuro (NF). Unit Pra lava flows Lawu 2 is composed of primary volcanic deposits pre-old Lawu quarter early. This is the oldest unit found in area research. The manifestation of hot water that appears in the unit is in the form of hot springs Jenawi, while hot springs Ngunut is at the limit of lithology among unit Genre Pre Lawu 2 and Formation Notopuro (Helmi et al., 2020). The picture 7 (a) consists of three layers. On layer first is rock marked clay with the color blue and green, have density 2.69 – 2.75 gr/cc is suspected as working rock cap for withholding fluid hot so as not go out to surface at a depth of 500 - 2500 m, layer second is marked pyroclastic lava rock color yellow with a density of 2.82 gr/cc expected as a reservoir at depths of 3000 - 4500 m, and lava marked color red with a density of 2.89 gr/cc expected as a heat source at a depth of 5000 - 8000 m.

In the 3D model (Figure 7 b) it can be seen sufficient structure complex under surface there is control fault system hot earth Mountain Lawu that is a fault that is next door south area study found there are 2 faults that control system hot earth Mountain Lawu in the form of hot springs Tasin as shown in figure 7. From the picture, a three-layer structure has a lower surface. Layer first is rock marked clay with the color blue and green, have a density of 2.69 – 2.75 gr/cc is suspected as cap rock at a depth of 500 - 2500 m, layer second is marked pyroclastic lava rock color yellow with a density of 2.82 gr/cc expected as a reservoir at depths of 3000 - 4000 m, and lava marked color red with a density of 2.89 gr/cc expected as a heat source at a depth of 5000 - 8000 m.

Based on the 3D results obtained if the second modelling combined in each region's hot springs so could see the correlation. Figure 7 (c) shows the correlation of results in the second mutual modelling cross. Second modelling, each other correlated with a good proved existence match on source hot area Mountain Lawu. Figure 7 (d) shows a correlation rock composer area study with a characteristic high rock volume value that is lava rock.



(a) (b)

(c) (d)

(e) (f)

Figure 7. 3D Modeling (a) In the area Ngunut and Jenawi (b) In the area Tasin (c) Correlation Results Fault (d) Correlation Result of Composing Rocks (e) (f) Continuity fault laterally area Ngunut, Jenawi and Tasin

In the 3D depth model (Figure 7 (e) (f)) it looks to result in a continuity structure system hot enough earth complex below the surface, this proved with existence a number of the controlling fault system hot earth area research, namely directional fault from northwest-southeast, west-east and north-south(Amalisana et al., 2017).

Conclusion

Based on the Land Surface Temperature map, the Mount Lawu area has a surface temperature ranging from 3.14 °C - to 23.25 °C, with manifestations in the form of Ngunut, Jenawi, and Tasin hot springs. In the 3D inversion modeling results obtained 3 rock layers, namely clay rock with a density of 2.69 – 2.75 gr/cc which is marked in blue and green and is suspected to be stamp rock at a depth of 500 - 2500 m, pyroclastic lava rock with a density of 2.82 gr/cc which is marked in colour. Yellow is suspected as a reservoir at a depth of 3000 - 4500 m, and lava with a density of 2.89 gr/cc marked in red at a depth of 5000 - 8000 m is suspected as a heat source.

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Conflicts of interest
The authors declare that there are no conflicts of interest.

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